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Contractor-Furnished Compaction Testing: Searching for Correlations Between Potential Alternatives to the Nuclear Density Gauge in Missouri Highway Projects

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Keywords

nuclear density gauge, light weight deflectometer, clegg soil impact hammer, Missouri Department of Transportation, MoDOT, quality management, design-build, design-bid-build, coefficient of determination, modulus, clegg impact value

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Contractor-Furnished Compaction Testing: Searching for Correlations Between Potential Alternatives to the Nuclear Density Gauge in Missouri Highway Projects.

by

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Abstract

The Missouri Department of Transportation's (MoDOT) past and present Quality Control and Quality Assurance programs for construction are examined. MoDOT's present Quality Management program along with a small number of grading projects has lowered the number of Quality Assurance (QA) soil compaction tests completed in the past two years. The Department would like to rid itself of using the Nuclear Density Gauges because of burdensome Federal regulations, required training, security and licensing fees. Linear and multiple regression analysis was performed to see if a correlation between nuclear density gauge dry densities values and Light Weight Deflectometer modulus values/ Clegg Hammer Clegg Impact Values exist. These relationships or lack thereof will determine the technology used by construction contractors to perform compaction quality control testing if MoDOT moves away from using nuclear density gauges for soil density verification.

Introduction

The Missouri Department of Transportation (MoDOT) began using design-build (DB) contracting in 2005. That business decision required a shift in the agency's quality management culture as many quality management (QM) tasks that had been performed by MoDOT staff were reassigned to the DB contractor (Gad et al. 2015). The Utah DOT described the change in the following manner.

> "The owner [UDOT] felt that one of the biggest challenges to the QC and QA program was "breaking the mold" of the traditional roles of the contractor and owner. The owner's personnel had all come from the "catch and punish" culture. Likewise the contractor personnel came from a similar background. To change philosophies to a more proactive quality role by the contractor and a less controlling oversight role of the owner was a significant challenge." (Postma et al. 2002).

Once that DB QM culture shift had been completed, MoDOT evaluated the results of the projects constructed using DB and found them to be as good as and often times better than the constructed quality of project delivered using traditional low bid design-bid-build (DBB). Hence, the agency made the decision to attempt to adopt its DB QM program on its DBB projects. The net result is that the amount of traditional quality control (QC) and quality assurance (QA) testing conducted by MoDOT personnel will be greatly reduced. It also calls into question whether MoDOT should continue to pay the life cycle operations and maintenance costs for QC testing equipment whose frequency of use has dropped off dramatically as a result of the change.

This paper reports the first step in making that transition from agency QM testing to contractor QM testing by MoDOT and documents the process followed to determine whether the change in QM philosophy also requires a change in the QC testing equipment used by both the agency and its construction contractor. Specifically, the paper will detail the results of testing and analysis completed to determine whether MoDOT construction contractors can continue to use their nuclear density gauges (NDG) to verify compaction if the agency chooses to abandon that device as too expensive to maintain given the reduced frequency of agency NDG compaction testing.

Background

The Missouri Department of Transportation (MoDOT) has been using the Nuclear Density Gauge (NDG) as its primary technology for compaction testing for nearly 35 years, and currently has about 56 units distributed across its seven districts. The NDG has been found to have the following primary benefits:

- Speed for obtaining the results.
- Requisite level of precision.
- Portable and compact.
- Measure both moisture and density.

The MoDOT changed its quality assurance (QA) program in 2013 and made the construction contractor responsible for the bulk of the quality control (QC) compaction testing. This process is termed Quality Management (QM) by MoDOT. The United States Nuclear Regulatory Commission (NRC) requires training, licensing and security that have become a hindrance to both MoDOT and the contractor. This role change, combined with a decreased number of major grading projects leads to the need to conduct considerably fewer tests, MoDOT therefore found it prudent to re-evaluate its use of the NDG in light of the large number of administrative requirements for training, certification, calibration, and storage. An internal study completed in 2014 estimated that the annual cost for operating and maintaining 52 field operated gauges NDG to be approximately $632,000 (McLain 2015). The frequency of nuclear density testing for the 2013 construction season running from March to November was established by sending a survey to the 29 MoDOT Resident Engineer (RE) offices in the state with 20 responses recorded. The same 20 offices were surveyed again for NDG usage for the 2014 construction season with 18 responses. The number of times the nuclear density gauge was used in the field per RE office during the construction season (approximately 32 weeks) has dropped from 37, approximately once a week to 22, which is roughly once every two weeks. That cost combined with reduced usage under the new QM program took the cost per test from $1881 to $3144 in the first year of the new QM program. Thus, an evaluation of alternatives to the NDG was authorized and the outcome is reported in this paper.

Table 1 MoDOT Resident Office NDG Usage

	2013	**2014**
Average time used per work week per RE office	1.16	0.68
Duration of tests (hrs)	1.26	1.20
Average NDG usage times per RE Office per construction season	37	22
Total duration of usage per RE (hrs)	46.65	26.35
Cost per test	$1881	$3144

MoDOT Quality Management Program Evolution

MoDOT’s definition of Quality Management (QM) is: “A process that gives the contractor the primary role and responsibility for incorporating quality into the project, where quality is included in the planning and scheduling of project activities. Quality is managed by the contractor with QC testing and inspection. QA by MoDOT is conducted at specified stopping or hold points.” (Ahlvers et al 2013).

MoDOT’s present QM system was an evolutionary process that began in 2000 when a QA/QC process for asphalt was initiated. Soon thereafter, MoDOT implemented a QA/QC program for Portland cement concrete pavements (PCCP). Next, the release of the *Missouri Standard Specifications for Highway Construction* (MSSHC) in 2004 increased QA/QC activity. MSSHC was developed to move the department towards increased usage of performance specifications (Ahlvers et al. 2013). The performance-oriented QM system originated in 2007 as a result of

MoDOTs initial large design-build (DB) projects. The pilot program was successful and the Department initiated full implementation of QM in 2013 on all projects.

Prior to 2000, the majority of the QC and all the QA activities were conducted by personnel from the MoDOT Construction and Materials Division on highway projects. This changed when MoDOT implemented a QA/QC program for asphaltic concrete pavement projects. The composition of the asphalt mixture was specified in MoDOT standard specifications, but the job mix formula was developed and submitted by the contractor for MoDOT approval. The contractor under the supervision of a MoDOT materials inspector would collect and submit samples of the asphalt binder and mineral aggregates to the MoDOT Central Laboratory for testing. If the tests on the samples passed, the contractor was then required to build test strips for each different mixture of a quantity of at least 2,000 tons to determine the compactive effort needed to obtain the required density. In all cases except stone mastic asphalt, MoDOT personnel performed asphalt pavement density testing using nuclear density measurements. Nominal thickness was tested by the Geotechnical Section with an auger truck equipped with water tanks and pavement core barrels. Past inspection and testing for PCCP was regulated by the MoDOT specifications as well and performed by MoDOT personnel with the contractor providing the field laboratory. Payment was based on results of profilograph measurements provided by the contractor with QA and pavement thickness measurements conducted by MoDOT.

Design-Build Quality Management

Atkinson (2005) found that quality in the DB project can be built into the project not added to the project as in DBB. The QA/QC process then morphed into a QM plan (QMP) for all processes on DB projects. QM was used with great success on the previously noted DB projects. The DB team was co-located with the MoDOT project team, where impromptu meetings could be held to solve problems that flared up quickly. The DB team included a full time QC manager who insured that construction means and methods complied with the specifications and that the materials installed met the submitted and MoDOT approved specifications. The QC Manager was not only in charge of the main contracting arm of the DB team but the myriad of subcontractors as well. The major change was that MoDOT inspectors worked with designbuilder's foremen and inspectors to perform quality management tasks at "hold or witness points" in the approved DB QMP.

New MoDOT Quality Management Program for Design-Bid-Build Projects

The DB QM procedures with several enhancements became the present DBB project QM system. The central elements of the MoDOT QM program for DBB projects are as follows:

1. The contractor employs a full time Quality Manager.
2. The contractor develops and utilizes a Quality Management Plan.
3. Certified technicians and inspection staff are provided by the contractor.
4. MoDOT provides the QA personnel for the project. (Ahlvers et al. 2013)

The QMP is the strategy for instilling quality into a project. Before the start of work the contractor must submit a draft QMP before the preconstruction conference. The project's Resident Engineer and the contractor meet to negotiate and iron out the details. When an agreement is reached a "final" QMP is signed thus making it a contractual document. This document can be revised to fit the needs of the project with further negotiations between the contractor and the Resident Engineer and District/Central Office Construction personnel.
The QMP contains an Inspection and Test Plan (ITP). MoDOT has established a base ITP with minimum testing frequencies. The contractor can advocate changes from the ITP testing frequencies. The changes are reviewed by the Resident Engineer and, depending on the proposed changes; the contractors' ITP may be reviewed by District and Central Office Construction staff. For materials sampling and testing the contractors' testing personnel must be listed in the quality management plan. If conflicts arise during inspection and testing an independent third party may be used to resolve the conflict. The contractor accepts and collects all material paperwork and tickets for materials delivered to the project site.

The MoDOT QM process addresses appropriate responses to any non-conforming work and deficient work that may occur. The definitions for these two categories are as follows:

- Non-conforming work: "Completed work that does not meet the contract requirements", (Ahlvers et al. 2013).

- Deficient work: “In-progress work that does not meet the contract requirements”. (Ahlvers et al. 2013.

A non- conformance report (NCR) keeps a record of deficient or non-conforming work. Either QC inspectors or QA inspectors can issue an NCR with an expectation that the QC inspectors will discover and issue the majority of the NCRs. With the issuance of an NCR, the contractor is required to propose a resolution to the problem. The QA inspector or Resident Engineer will approve or disapprove the proposed resolution and once the NCR is resolved MoDOT closes the issue.

Evaluation of Alternatives

The initial evaluation of alternatives involved the following classes of non-nuclear testing devices posited by Berney and Kyzar (2012):

1. Electrical Density and Moisture Gauges
    a. Electrical Density Gauge (EDG)
    b. Soil Density Gauge (SDG)
2. Volume Replacement/Volume Measurement
    a. Balloon (RB)
    b. Sand Cone (SC)
    c. Density Drive Sampler (DDS)
3. Stiffness/Modulus Measurement
    a. Light Weight Deflectometer (LWD)
    b. Dynamic Cone Penetrometer (DCP)
    c. Clegg Soil Impact Tester (Clegg Hammer)
    d. GeoGauge (GG)

This paper focuses on the relationship of the Light Weight Deflectometer and the Clegg Soil Impact Tester (a.k.a. Clegg Hammer) and how they correlate with the NDG dry density results in differing materials. This relation discussed in the paper can affect the contractors’ QC process if MODOT elects to uses the Clegg Hammer or the LWD to measure the modulus and the contractor wishes to test compaction with the NDG.

Density Testing Requirements in the New QM Program

The ITP mandates a minimum QC density testing frequency of one test per lift per 500 feet per activity. Under the specification an activity is defined as predetermined item of work in a distinct location. The minimum QA density testing frequency is one test per day. These testing frequencies are for both the placement and compaction of embankment and compaction in cut. The approved tests for compaction according to Section 203 of the MSSHC are AASHT0 T 191 (Sand Cone), AASHTO T 205 (Rubber Balloon), and AASHTO T 239 (Nuclear Density Gauge) with the nuclear density gauge being both the preferred and most often used testing method. However, the new QM program requires less involvement by MoDOT personnel, which calls into question the continuing cost effectiveness of maintaining two nuclear density gauges (NDG) in each RE office. Before the new QM program was implemented and MoDOT personnel were conducting QC density tests, an argument could be made that the results of the tests needed to be available as soon as practical to facilitate the identification of nonconformance with compaction standards and their remedies in a manner that did not compromise the contractors' production. Nonetheless, the shift of all QC testing to the contractor made it the master of its own destiny and removed MoDOT from the production interruption equation. Therefore it is important to compute the change in NDG usage by MoDOT personnel both before and after the QM program change.

The costs per test shown in Table 1 were generated by dividing calculated equivalent uniform annual cost (EUAC) for ownership, operation, security and maintenance of MoDOT's NDGs by the average usage times in a construction season. The program to initiate QM on all projects has successful. As with any new initiative, there has been a learning curve for both contractors and MoDOT personnel. Now, with two construction seasons completed under the QM directive, procedures and responsibilities for both QA and QC have been learned, discussed and adjusted as required. There is a desire in the department to change compaction testing methods and do away with the NDG. To make the decision, MoDOT needed to evaluate the life cycle cost of current alternative technologies and compare that to the life cycle cost of adopting emerging technology that is compatible with Intelligent Compaction (IC) construction processes. The different alternatives will influence what MoDOT's contractors are allowed use for QC compaction testing. Their choice of testing technology will need to produce a measurement that is either the same property as the MoDOT technology or a well-defined correlation between different properties reported by different test methods. The non-nuclear Soil Density Gauge (SDG) readings are the same as the NDG (dry density and percent moisture). Thus, the contractor could still use the NDG for soil compaction QC if MoDOT adopted the SDG. The Modulus/Clegg Impact Value (CIV) based testing also has shown promise and has been implemented by several departments of transportation.

Research Objective

However, if MoDOT and its contractors use different technologies, a reliable correlation must be established between these modulus/CIV based testing procedures and density reported by the contractor's NDG or the contractor will most likely be required to utilize its own modulus/CIV based testing equipment for QC tasks. If no correlation exists then both compaction testing QA and QC will have to be conducted with the same method and/or equipment. Therefore the research objective is to answer the following question:

> *Can contractor quality control compaction testing on MoDOT construction projects be completed using the NDG while MoDOT quality assurance compaction verification tests are taken with a non-NDG technology?*

Earlier research studies have investigated the relationship between NDG readings and modulus/ stiffness/CIV readings, Intelligent Compaction Measurement Value (ICMV) and machine drive power (MDP), which includes Steinart et al. (2005), Hossain and Apeagyei (2010), Thompson and Schmitt (2013) and Ganju et al. (2015). In Meehan et al. (2012), the research team used a simple linear regression approach to determine if a relationship exists between NDG dry density results and modulus readings from the light weight deflectometer (LWD), dynamic cone penetrometer (DCP), and the Humboldt GeoGauge (GG) (a.k.a as the Soil Stiffness Gauge) and the results are shown in Table 7-4. The coefficients of determination display either a low correlation between the NDG and the DCP readings (0.22 -0.40) or essentially no correlation between NDG and the modulus readings for the LWDs and the SSG (0.068- 0.026).

Table 2 Coefficient of Determinations from Linear Regression Comparisons with NDG (Meehan et al. 2012)

Dependent Variable	Coefficient of Determination (R^2)
Soil Stiffness Gauge SSG/ GeoGauge GG	0.027
LWD 300	0.026
LWD 200	0.068
DCP -M	0.40
DCP-A	0.22
Notes: LWD 200 = Zorn LWD plate diameter of 200 mm; LWD 300 = Zorn LWD plate diameter of 300 mm; DCP-A = average; DCP-M = weighed mean; Method from White et al. (2007); Results from embankment constructed with sandy silt soil (SM)	

Similar results were found by Li (2013) in which linear regression was used in the comparison of the NDG Dry Density results to LWD modulus, GG stiffness, DCP California Bearing Ratio (CBR) , and modified Clegg Hammer results (MCH).The coefficients of determination varied with device compared, material tested and density of that material shown in Table 7-5.

Table 3 Coefficient of Determination from Comparisons to NDG from 3 Michigan Test Sites (Li 2013)

Location	Material	R^2 GG	R^2 LWD	R^2 DCP	R^2 MCH	Comments/Notes
Hancock	Gravel	0.26	0.019	0.22	0.010	Uncompacted test pads
Calumet	Gravel	0.98	0.41	0.70	0.70	Fully compacted test pads
Iron River	Sand	0.032	0.10	0.14	0.19	Fully compacted test pads with IC roller

The author noted that the poor correlation between the NDG and the other devices at the Hancock site could have resulted from the fact that test pad was uncompacted and only four measurements were taken. The author also commented that the good correlations for the tests conducted at the Calumet site might not be representative due to the limited number of tests (4) and that further assessment was needed. The author concluded that simple regression analysis did not show good correlation for the tests conducted on sand at the Iron River site due to soil heterogeneity and moisture content variation.

Meehan et al. (2012) and Li (2013) demonstrated that coefficients of determination can improve by the use of multiple regression analysis in which moisture or Intelligent Compaction (IC) factors such as amplitude, vibration frequency and roller speed are considered. The introduction of compacted moisture content vastly improved the correlation of the nuclear gauge to the other compaction test devices as compared to linear regression seen in the table below.

Table 4 Multiple Regression Analysis That Includes the Effect of Compaction Moisture Content (Meehan et al. 2012)

Dependent Variable	Coefficient of Determination R^2
Soil Stiffness Gauge SSG/ GeoGauge GG	0.27
LWD 300	0.48
LWD 200	0.44
DCP -M	0.58
DCP-A	0.57

Table 5 Comparisons of Simple and Multiple Regression Analysis for ICMV and Point Measurements of Gravel at Iron River Site (Li 2013)

	IC & NDG	IC & GG	IC & LWD	IC and DCP	IC & MCH
R^2 Simple Regression	0.0008	0.0010	0.17	0.06	0.0001
R^2 Multiple Regression	0.63	0.61	0.63	0.76	0.61

Additionally, multivariate regression of the same data does increase the correlation between NDG readings and modulus/stiffness readings, but introduces anther level of complexity into the calculation/comparison of NDG density readings to modulus readings. This process would be difficult for the average construction inspector to generate.

Methodology

If MoDOT (QA) and contractors (QC) use different compaction measurement systems, there must be a relation or correlation between modulus measurements with density measurements. To establish if two variables are related one must build an empirical model based on observed data. The following empirical model is developed from a scatter diagram of NDG data and density data from the TransTech Soil Density gauge, CIV data from the 10 KG Clegg Impact Hammer and modulus/ stiffness data from the LWD and DCP. From Montgomery, Runger and Hubele (2007), if a relationship exists between two variables then a response variable Y is related to a regressor or predictor variable x in a simple linear regression model described by Equation 1:

$$Y = \beta_0 + \beta_1 x + \varepsilon \qquad (1)$$

Where: β_0 and β_1 are unknown regression coefficients and

ε is a random error.

For the Equation 1 linear regression model, there is an expected value of Y for each value of x. β_0 is the Y axis intercept and β_1 is the slope of the line or the mean change in Y for a unit change in variable x. The linear regression consists of finding the best fit straight line through the points on the scatter plot. This best fit line is determined using by minimizing the sum of the squares of the vertical deviations. This estimation process used to determine β_0 and β is called the method of least squares. For this study, the independent variables or predictors are the NDG dry densities with the dependent variables being LWD modulus values or Clegg impact values (CIV).

MoDOT conducted these comparison tests in order to become familiar with the alternate testing devices, testing procedures, testing times, costs, and ease of use. An additional goal of the tests was to provide valid local results in which road construction contractors may have confidence. The series of comparative tests were conducted at locations on active or recent grading projects. The sites and soil properties are shown below.

Table 6 Testing Locations, Soil Type and Standard Proctor Results

Location	Soil Type (USCS)	Average Dry Density kg/m^3 (pcf)	Average Moisture Content (%)	MDD kg/m^3 (pcf) [OM(%)]
Capital Quarries Cole Co.	SP	1722.0 (107.5)	6.7	2098.4 (131) [12]
Discovery Parkway Boone Co.	CL	1806.9 (112.8)	15.1	1786.0 (111.5) [15.5]
Route 50 Osage C0. East CO. RD 401 and 604	CH	1667.5 (104.1)	12.3	1681.9 (105) [16]
Route 50 Osage C0. East Co Rd 602	CH	1678.7 (104.8)	14.5	1697.9 (106) [16]
USCS: Unified Soils Classification System; MDD: Maximum Dry Density ; OM: Optimum Moisture				

The tests were usually conducted in the following manner with some changes depending on the devices being tested.

1. The test location was smoothed out and the first test was conducted with the TransTech Soil Density Gauge (SDG). The SDG measures dry density in pound per cubic foot (pcf) and moisture content of the soil in percent.
2. A pilot hole for the NDG probe was driven in the middle of the test area.
3. The NDG was placed and the probe extended into the hole.
4. The first compaction test was run for a 4 minute count. The Troxler Nuclear Density Gauge used measures dry density in units of pounds per cubic feet (pcf) and moisture of the soil in percent.
5. After the first test was complete the NDG was turned 180 degrees and another 4 minute test was run.
6. A Zorn LWD with a 300 mm plate was placed over the outline of the first NDG test and a standard six drop test was conducted. The German manufactured Zorn records modulus in units of Meganewtons per meter squared (MN/m^2) and settlement in millilmeters.
7. A 10 kg ,Clegg Hammer, 4 drop test was conducted over the outline of the second NDG test. Readings are taken in tens of gravities or Clegg Impact Values.

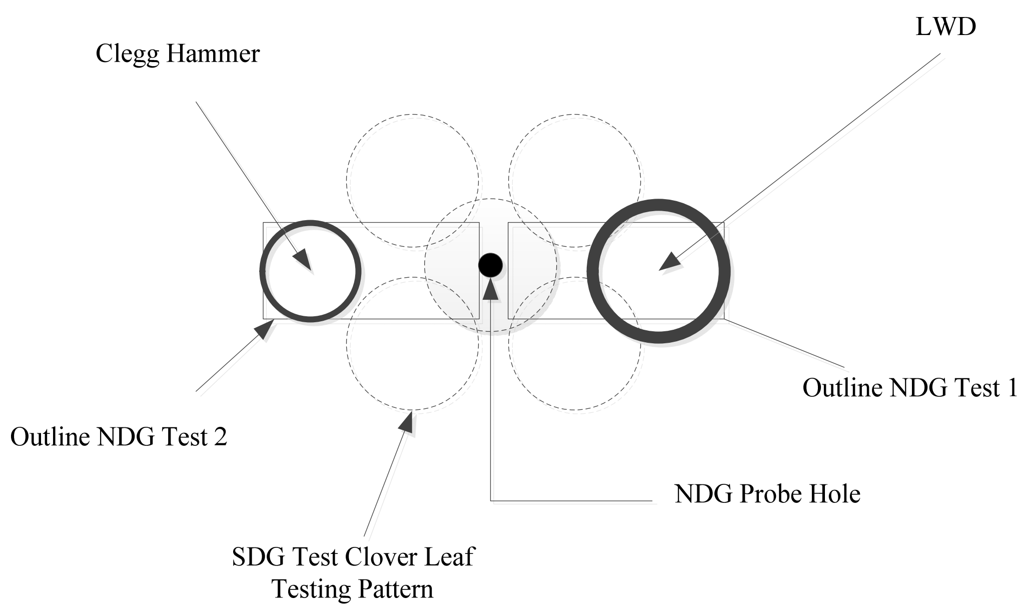

Figure 1 Compaction Testing Evaluation Configuration

The Zorn LWD measures a force pulse produced by a falling 10 kg mass onto a spring assembly that transmits the load pulse to a 300 mm diameter plate resting on a soil. The plate deflection is then measured in millimeters. The drop height is preset by the manufacturer and it is recommended not to be changed by the user. The dynamic deflection modulus for the Zorn is calculated by using the following formula:

$$E_{VD} = \frac{22.5}{s} \qquad (2)$$

Where: E_{VD} = Dynamic Deflection Modulus (MN/m^2)
s = Settlement (mm)

Six drops are performed per test site. The first three drops are seating drops. The average settlement for the last three drops is calculated and then an average dynamic modulus is calculated using equation 2 (Zorn 2005).

Clegg Impact Value is measured from dropping a weight or hammer instrumented with an accelerometer. A 10 kg hammer was used evaluating the compacted soils. The 10 kg hammer is most applicable for stiff or machine compacted soils. The Clegg Impact Value (CIV) is expressed in units of tens gravities derived from peak deceleration of the falling hammer. Three free falling blows to the soil are delivered in succession from the top of the guide tube. The CIV is the highest value of the recorded four blows. Like the modulus value from the LWD, the recorded CIV value is not a percentage of compaction but a strength index value for a particular moisture value (ASTM D5784).

To determine the strength of the relationship between x and y or how well the data fits the regression line the coefficient of determination is used. The coefficient of determination ranges for 0 to 1. An R^2 of 0 means that y cannot be determined from x. An R^2 of 1 means that y can be predicted from x without error. A coefficient determination of 0.8 means that 80 percent of the variation can be explained by the linear relationship between x and y while the other 20% is unexplained. Table 7 shows the calculated coefficients of determination for samples taken in the same locations using the two different compaction testing devices.

Table 7 Linear Regression Results

Location	Dependent Variable	Independent Variables	Linear Equation	R^2
Capital Quarries Cole Co.	LWD modulus	Dry Density (DD)	Evd= -156.57 + 2.082(DD)	0. 36
Discovery Parkway Boone Co.	LWD modulus	Dry Density (DD)	Evd= -93.672 + 1.0748(DD)	0.11
Route 50 Osage C0. East CO. RD 401 and 604	CIV	Dry Density (DD)	CIV = 12.846 + 0.022(DD)	0.0024
Route 50 Osage C0. East Co Rd 602	CIV	Dry Density (DD)	CIV =17.56 + 0.2588(DD)	0. 68

As mentioned previously, multiple regression (a.k.a. least squares multiple linear regression) generates better predictions than simple linear regression. A multiple regression equation can take the form shown in Equation 3:

$$\text{Dependent Variable} = C0 + V1 \times C1 + V2 \times C2 + ... + Vn \times Cn \tag{3}$$

Where: C0 =Intercept value

V1 = Value of first independent variable

C1 = First coefficient linked to first independent variable

V2 = Value of second independent variable

C2 = Second coefficient linked to second independent variable

n = number of independent variables

For multiple linear regression models for comparisons between Modulus values/Clegg Impact Values (CIV) and dry density (DD) and percent moisture (m %) results in Equation 4:

$$\text{Modulus Values/Clegg Impact Values (CIV)} = C_0 + DD \times C_1 + m\% \times C_2 \tag{4}$$

Multiple regression analysis was run using a commercial spreadsheet. In order to validate the mode, 70 percent of the compared values are used to build the multiple regression models, while the remaining 30 percent of the comparisons were reserved to evaluate the model’s performance. When going through the validation steps using Microsoft Excel, p-values are calculated for the generated model. Low p-values $p< 0.05$ indicates that the independent variable is expected to be a significant addition to the model because changes in the independent variables value are associated to changes in the dependent variable. When maximizing the coefficient of determination, independent variables with p values greater than 0.05 should be removed from the equation. Generally the p values for percent moisture were greater than 0.05 but were not removed because the purpose of the multiple regression was to assess the effects of moisture on the prediction of modulus or CIV values.

Table 8 Multiple Regression Results

Location	Dependent Variable	Independent Variables	Linear Equation	R^2 (p value moisture)
Capital Quarries Cole Co.	LWD modulus	Dry Density (DD) %Moisture (%M)	Evd= -36.7169 + 1.566674(DD) - 9.64184(%M)	0.28 (0.41)
Discovery Parkway Boone Co.	LWD modulus	Dry Density (DD) %Moisture (%M)	Evd= 153.1378 - 0.87329(DD)- 1.63597(%M)	0.28 (0.24)
Route 50 Osage C0. East CO. RD 401 and 604	CIV	Dry Density (DD) %Moisture (%M)	CIV = 2.518564 + 0.12262(DD) - 0.40817(%M)	0.30 (0.0089)
Route 50 Osage C0. East Co Rd 602	CIV	Dry Density (DD) %Moisture (%M)	CIV = -32.5083 + 0.374489(DD) + (0.183126)(%M)	0.78 (0.38)

A commercial neural network program was also used to make predictions for CIV and LWD modulus readings from a data set of nuclear gauge dry density and moisture readings. Neural Networks represent the state-of-the-art in artificial technologies in solving problems (Leung et al. 2000). Neural networks can serve an alternate to more conventional statistical methods. Similar to linear regression they can be used for approximation purposes. Neural networks are based on the structure of the brain, where the network contains elements which receives a number of inputs and generates an output. The network is initially trained from the data points and the relationship between the points. The network can then predict a value from data fed into it. The computer program used defaults to training with 80 percent of the variables and testing with remaining 20 percent of values.

Two different types of neural nets were used employed in examining correlations between the independent dry density and moisture content and the dependent LWD modulus readings and Clegg Impact Values. The first network used applied was a Multi-Layered Feedforward Network (MLF) also known as a Multi-layer Perception Network (MLP). The MLF structure used contained input nodes which represent the dependent variable(s). Two hidden layers process the data and generate an output. The MLF net can take time and computing power to produce, but can compute generalizations from small training sets. Generated coefficients of determination shown in Table 9 were generated as a comparison parameter with the linear and multivariate results and to generalized regression neural networks (GRN).

Table 9 MLF Neural Network Results

Location	Dependent Variable	Independent Variables	Linear predictor in Training R^2
Capital Quarries Cole Co.	LWD modulus	Dry Density (DD) (pcf)	0. 10
Capital Quarries Cole Co.	LWD modulus	Dry Density (DD) (pcf) Moisture (%M)	0.37
Discovery Parkway Boone Co.	LWD modulus	Dry Density (DD) (pcf)	0.09
Discovery Parkway Boone Co.	LWD modulus	Dry Density (DD) (pcf) Moisture (%M)	0.72
Route 50 Osage C0. East CO. RD 401 and 604	CIV	Dry Density (DD) (pcf)	0.03
Route 50 Osage C0. East CO. RD 401 and 604	CIV	Dry Density (DD) (pcf) Moisture (%M)	0.17
Route 50 Osage C0. East Co Rd 602	CIV	Dry Density (DD) (pcf)	0.62
Route 50 Osage C0. East Co Rd 602	CIV	Dry Density (DD) (pcf) Moisture (%M)	0.64

The second neural network applied was the GRN network. The GRN network contains inputs for each independent numeric variable. Inputs are carried to a pattern layer. Each node in the pattern layer calculates the distance from the presented values. From the pattern layer values are sent to the summation layer which contains nodes designated as numerator and denominator nodes. The summation layer nodes are functions the distance to the pattern layer and the dependent node. The summation nodes sum up inputs while the output later divides the value in half. The advantage of GRN net is that the net trains extremely fast. GRN results are shown in the table below.

Table 10 GRN Neural Network Results

Location	Dependent Variable	Independent Variables	Linear Equation	Linear predictor in Training R^2
Capital Quarries Cole Co.	LWD modulus (	Dry Density (DD)	Evd= -146.37 + 1.97(DD)	0.33
Capital Quarries Cole Co.	LWD modulus	Dry Density (DD) Moisture (%M)	Evd= -88.19 + 1.675(DD) – 3.33(%M)	0.53
Discovery Parkway Boone Co.	LWD modulus (	Dry Density (DD)	Evd= -103.20 + 1.16(DD)	0.11
Discovery Parkway Boone Co.	LWD modulus	Dry Density (DD) Moisture (%M)	Evd= 139.90 – 0.26 (DD)- 5.42(%M)	0.38
Route 50 Osage C0. East CO. RD 401 and 604	CIV	Dry Density (DD)	N/A	.0015
Route 50 Osage C0. East CO. RD 401 and 604	CIV	Dry Density (DD) (Moisture (%M)	CIV = 10.16 + 0.04(DD) - 0.30(%M)	0.17
Route 50 Osage C0. East Co Rd 602	CIV	Dry Density (DD)	CIV = -16.61 + 0. 25(DD)	0.71
Route 50 Osage C0. East Co Rd 602	CIV	Dry Density (DD) Moisture (%M)	CIV = -14.85 + 0..24(DD) – 0.09 (%M)	0.66

The neural networks produced coefficient of determinations that were in the order of the linear regression and multivariate regression results with the two independent variable trained nets typically having higher coefficients of determination.

Conclusions

The conclusions reached in this study are as follows:

- The results from linear regression, multiple regression and MLF and GRN neural nets show that there is no definitive relationship between LWD modulus and Clegg CIV values in both lean clays to clays (Route 50, Osage Co. & Discovery Parkway, and Boone County) and in sand (Capital Quarries, Cole Co.).
- The Clegg did show moderate relationship to the NDG density with coefficient of determination values of 0.676 (simple linear regression) and 0.780453 (multiple regression) and an average 0.66 for neural net cases of at the testing site east of County Rd 602 on the Route 50 Project.

- However the Clegg and NDG density had a very poor to poor relationship at another site on Route 50 project (east of CO. Rd 401 and 604) with R^2 values of only 0.0024 from simple linear regression and 0.3046 with a multiple regression analysis. Average Neural network R^2 values were found to be 0.37.

Therefore no definitive relationship between NDG and Modulus/CIV results could be found from Missouri test sites. This confirms the findings of Meehan and Li and others, and leads the authors to conclude that in the QM process for testing compaction of soils in embankments and cuts, both QC an QA must be verified with the same testing apparatus and method. Therefore, if MoDOT decides to cease using the NDG for QA compaction testing and utilize strictly modulus/stiffness measurements then its contractors will no longer be able to use the NDG.

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IJQI-108280 Reviewer Response Form

Reviewer	Reviewers Comments	Action Taken
Reviewer A	A lot of work is already done on developing correlations between soil stiffness parameters (CIV, LWD, etc) with soil density/strength parameters, so add more references other than Missouri Department of Transportation and preferably most recent ones. Understand the different working principle of the equipment used for this study and incorporate this difference while justifying the observed soil behavior.	Added more reference regarding correlations of Nuclear Density Gauge measurement not only to modulus but to Intelligent Compaction values as well. Also added discussion of measurement values of differing compaction measuring instrumentation used.
	The trend of data using linear regression, multiple regression and neural networks needs to be explained by performing more detailed analysis.	Added differing neural network calculation methods and discussion as seen in Tables 9 and 10 which follows the trend of the linear and multivariate regression results.
	Improper formatting and unnecessary gaps in the paper has been observed at number of places that need to be corrected. Soil symbol/name should be used according to some classification system.	This has been corrected.
	Equations 1 must be corrected	The equation has been corrected
	State the exact p value obtained for moisture content while performing multiple regression technique.	p value obtained was added to Table 8.
	Testing locations have been mentioned in tables. Add the soil type, data for soil classification and its degree of compactness for each case.	Soil type, average density, average moisture content along maximum dry density and optimum moisture has been added. See Table 6.
Reviewer B	The introduction portion is well written and reflect different studies conducted in different US States over a period of time. Authors have discussed different aspects of quality control. Overall, the material is good, but it needs refining and duff tailing	Authors have refined introduction and abstract as well as adding more neural network explanation and employing differing evaluation methods offered by the neural network computer program used for correlation evaluation. The title has also been

	in the light of main objectives of the study.	changed to reflect the true intent of the paper.
	The methodology section is week. Author should add more test areas and soil types to make the findings more general. All figures and tables need proper illustration and meaningful discussion. The study is limited to Mo Dot soil. Most recent papers are required to cite in the paper.	The test areas were representative of the type of soils most encountered within the state of Missouri. The Testing was completed on active Missouri road and private construction jobs. The research was funded by the Missouri Department of Transportation, out of state sites were not in the scope of this study. Correlation attempts between
Reviewer C	Data points are very few. By increasing the data points, possibility of developing correlations with a suitable value of coefficient of determination.	Data points were collected for four different areas. The correlations fell in line with cited authors Meehan's and Li's findings as well as other cited reports, that there is no correlation between nuclear density gauge readings and recorded modulus or Clegg Impact Values.
	Confidence levels, F distribution and t distribution for the developed models are needed to show.	F and T distribution are good suggestions but are not part of the model proposed or used. Regression analysis can be understood by most Missouri Department of Transportation and contractor construction inspection managers and practitioners.
	Same system of units must be used, i.e., SI or FPS. Please refer to Figure 2. Here the modulus value is in SI system and density in pcf. Here use of same system of units is suggested.	Figure 2 has been removed. Explanation between differing systems has been introduced in the paper explaining the use of American and German Instrumentation. Density in both SI and English is used in Table 6.
	The quantum of referred articles are very few, some more references should be included in the paper	More correlation of density to modulus and intelligent compaction values have been added as well as references related to neural networks.